
Davis
Dirac
Fermi
Majorana
Pauli
Pontecorvo
Reines
Koshiba
photo PRB
Goeppert-Mayer

Double Beta Decay

Is the Neutrino Mass within Reach?

Steve Elliott

Outline

What is ββ?

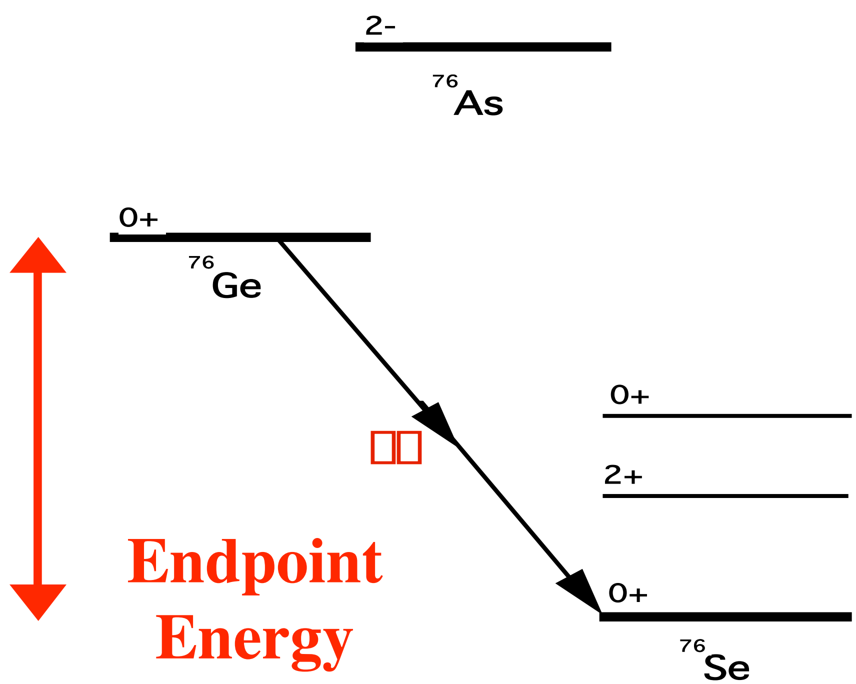
What is the interesting m_{ν} region for ββ?

The upcoming experiments will be sensitive to that region.

The Matrix Elements are uncertain.
Leads to a problem we'd like to have.

Conclusion

Example Decay Scheme



In many even-even nuclei, β decay is energetically forbidden. This leaves ββ as the allowed decay mode.

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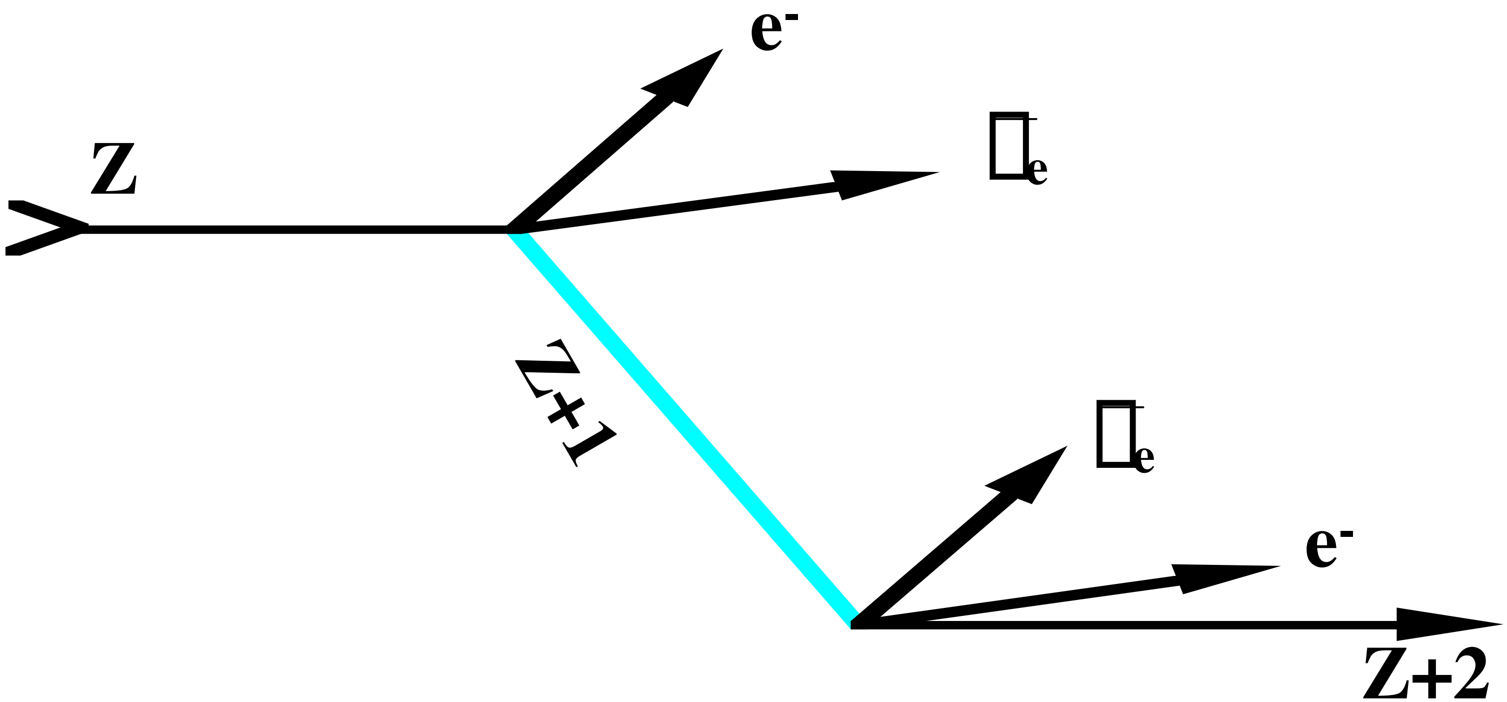
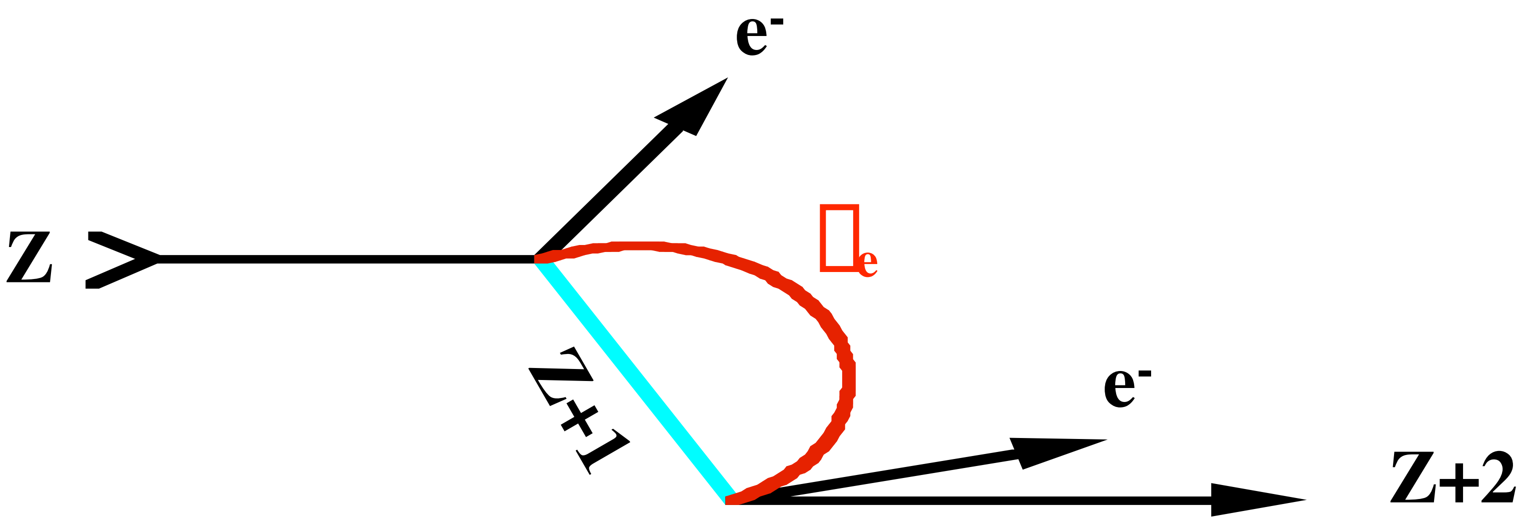
ββ(2ν): Allowed weak decay



$$2n \to 2p + 2e^- + 2\bar{\nu}_e$$

ββ(0ν): requires massive Majorana ν



$$n \rightarrow p + e^- + \bar{\nu}_e$$

(RH $\bar{\nu}_e$) (LH ν_e)

$$\nu_e + n \rightarrow p + e^-$$

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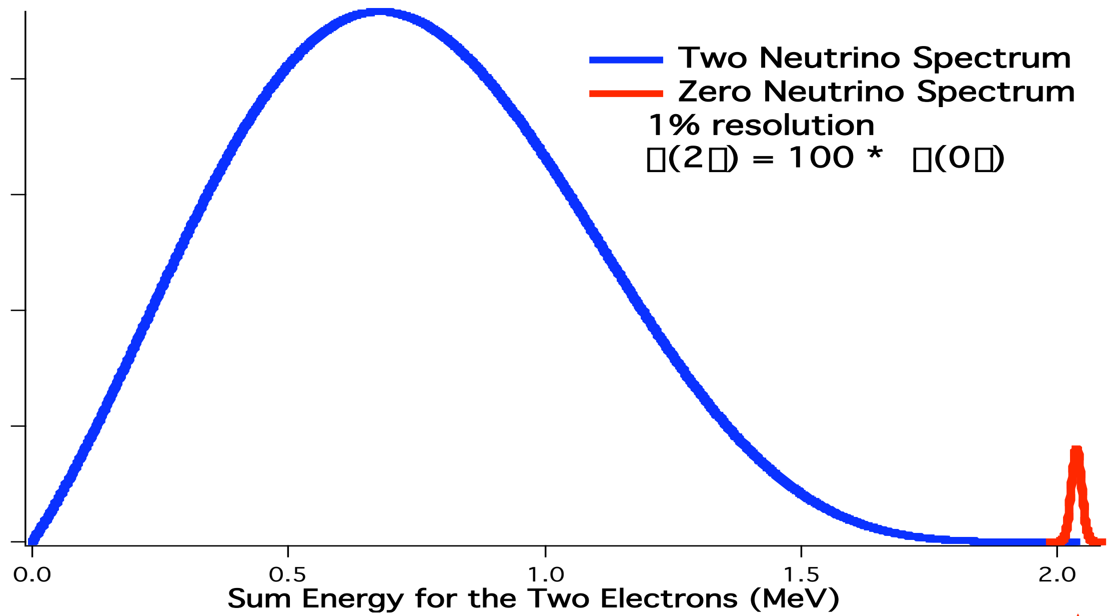
Energy Spectrum for the 2 e^-



Endpoint Energy

ββ History

ββ(2ν) rate first calculated by Maria Goeppert-Mayer in 1935.

First observed directly in 1987.

Why so long? Background

$$T_{1/2}(\mathrm{U, Th}) \sim T_{universe}$$

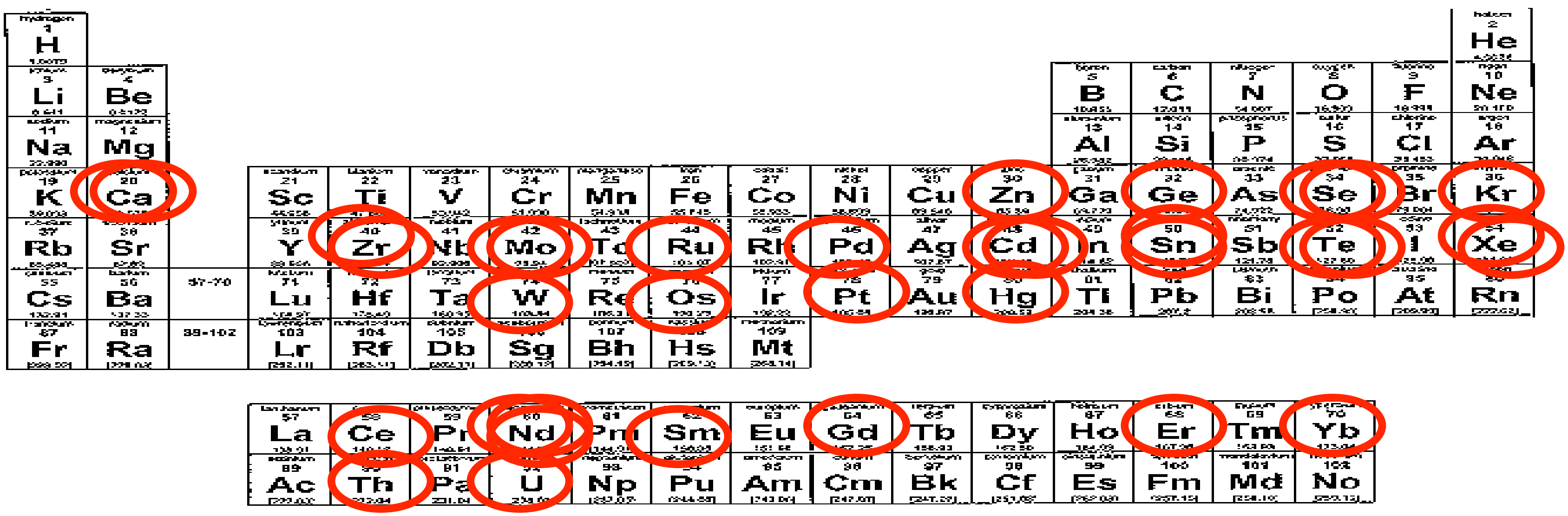
$$T_{1/2}(\beta\beta(2\nu)) \sim 10^{10}\ T_{universe}$$

But next we want to look for a process with:

$$T_{1/2}(\beta\beta(0\nu)) \sim 10^{17}\ T_{universe}$$

□□ Candidates

There are a lot of them!



How to choose a □□ isotope?

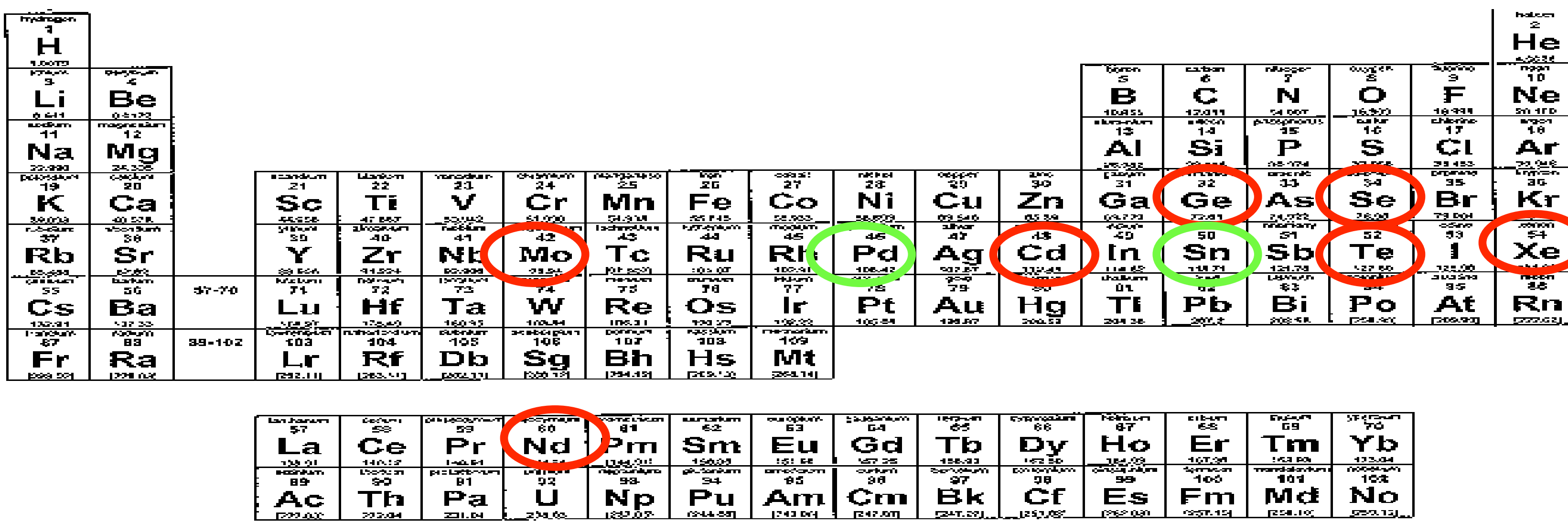
Detector technology exists

High isotopic abundance or an enriched source exists.

High energy = fast rate

High energy = above background

□□ Candidates
Abundance > 5%,Trans. Energy > 2 MeV



Frequently studied isotope.

ββ Decay Rates

$$\Gamma_{2\nu} = G_{2\nu}\left|M_{2\nu}\right|^2$$

$$\Gamma_{0\nu} = G_{0\nu}\left|M_{0\nu}\right|^2 m_{\nu}^2$$

G are calculable phase space factors.

$G_{0\nu} \sim Q^5$

|M| are nuclear physics matrix elements.

Hard to calculate.

m_{ν} is where the interesting physics lies.

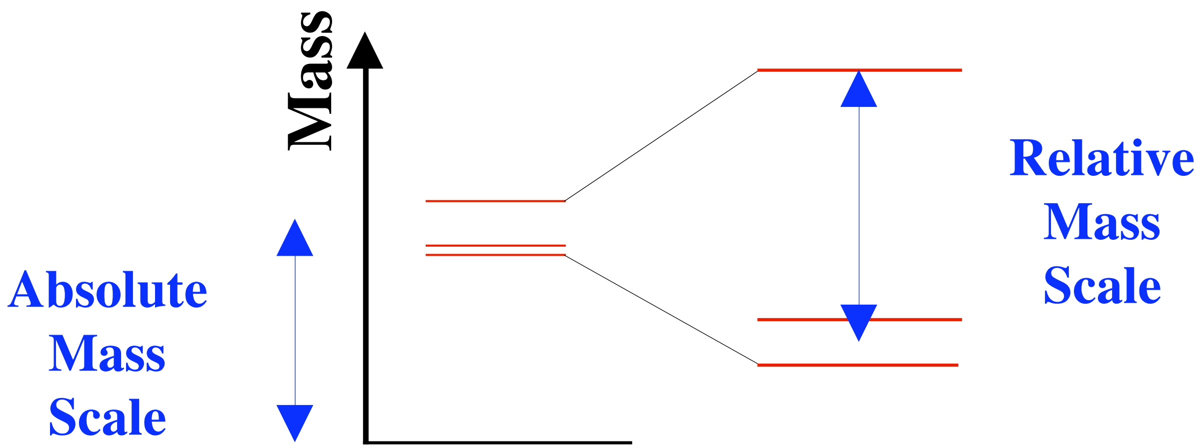
Why is m_ν interesting?

Neutrino mass is physics beyond the standard model of particle physics. The mass and mixing provides clues to the underlying structure of particle physics.

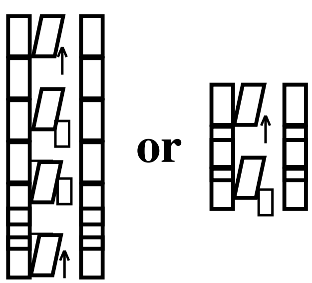
Neutrino mass and mixing play an important role in astrophysics and cosmology.

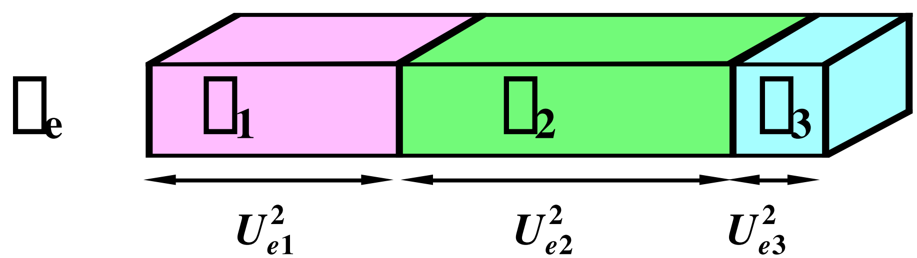
- light nuclei formation in big bang
- large scale structures in the universe
- supernova explosion dynamics
- R-process production of nuclei
- dark matter

Neutrino Mass: What do we want to know?



Dirac or Majorana





Mixing

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Neutrino Mass: How do we learn what we want to know?

	Absolute Mass Scale	Relative Mass Scale	Mixing Matrix Elements	CP nature of □
□□	✓			✓
□	✓			
Oscil.		✓	✓	

Need all 3 types of experiments.

Neutrino Masses: What do we know?

The results of oscillation experiments **indicate ν do have mass!**, set the relative mass scale, and a minimum for the absolute scale.

β decay experiments set a maximum for the absolute mass scale.

$$50\ \text{meV} < m_{\nu} < 2200\ \text{meV}$$

We also know ν mix.

The weak interaction produces ν_e, ν_μ, ν_τ.

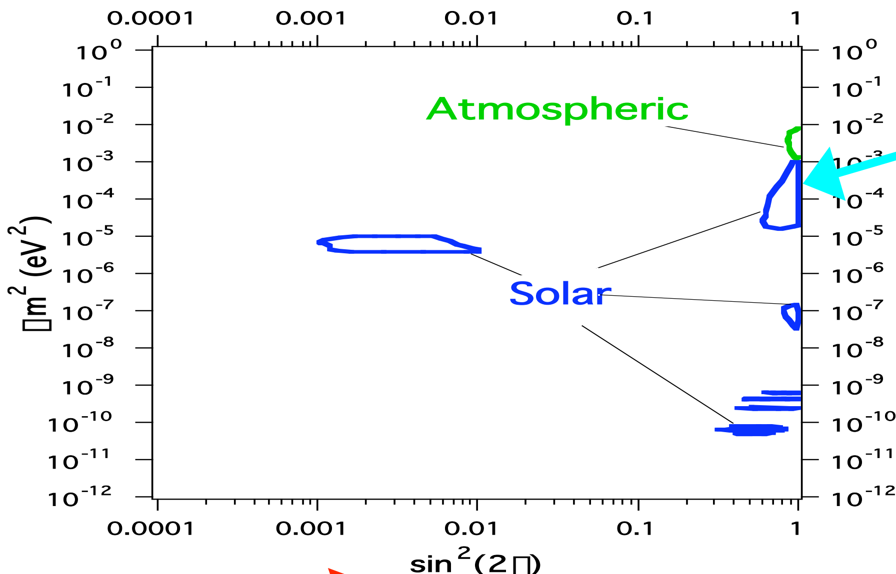
These are not pure mass states but a linear combination of mass states.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Oscillation experiments indicate that ν mix and constrain $U_{\alpha i}$.

The Relative m_ν Scale

$$\Delta m^2 = m_2^2 - m_1^2$$



LMA:

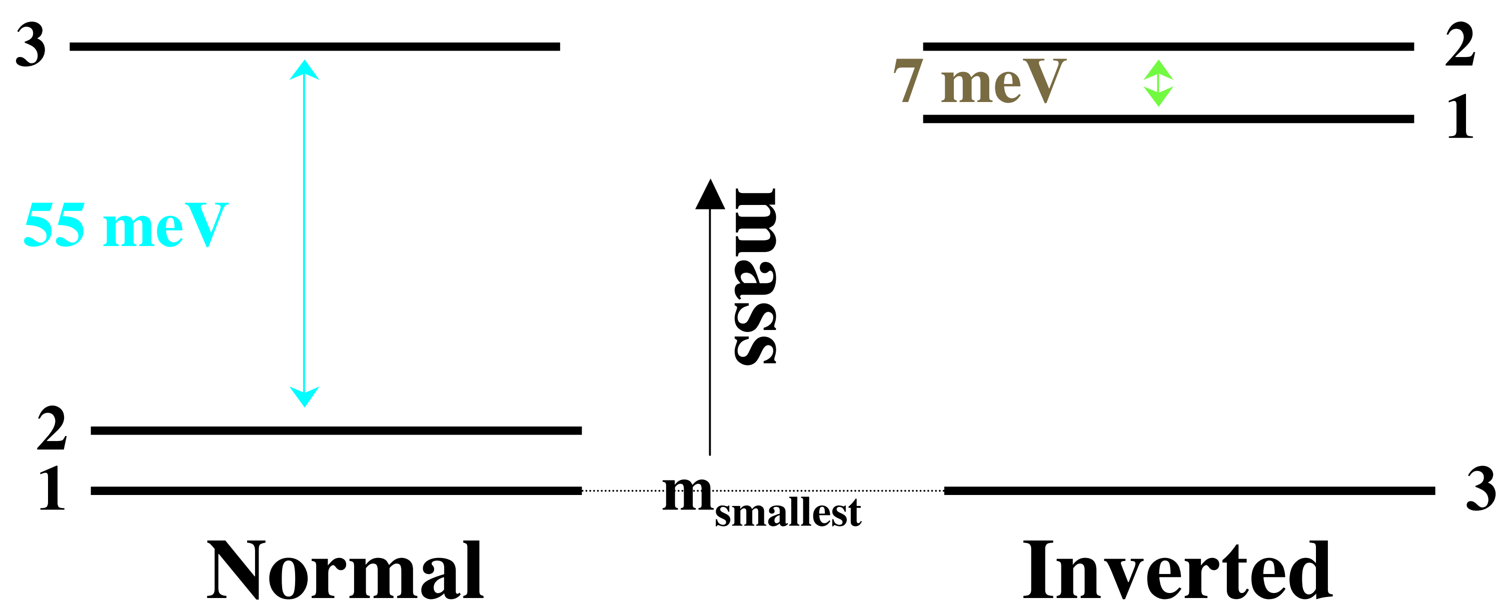
This region is preferred by the solar ν and KamLAND results.

Related to $U_{\nu i}$

$$\Delta m^2_{\mathrm{atm}} \approx 3x10^{-3}\, eV^2 = (55\ meV)^2$$

$$\Delta m^2_{\mathrm{LMA}} \approx 5x10^{-5}\, eV^2 = (7\ meV)^2$$

Oscillations and Hierarchy Possibilities



ν_e is composed of a large fraction of ν_1.

What about mixing, m_ν & $\beta\beta(0\nu)$?

No mixing: $\langle m_{\beta\beta} \rangle = m_{\nu_e} = m_1$

$$\langle m_{\beta\beta} \rangle = \sum_{i=1}^{3} \left| U_{ei} \right|^2 m_i \varepsilon_i$$

virtual ν exchange

$\varepsilon = \pm 1$, CP cons.

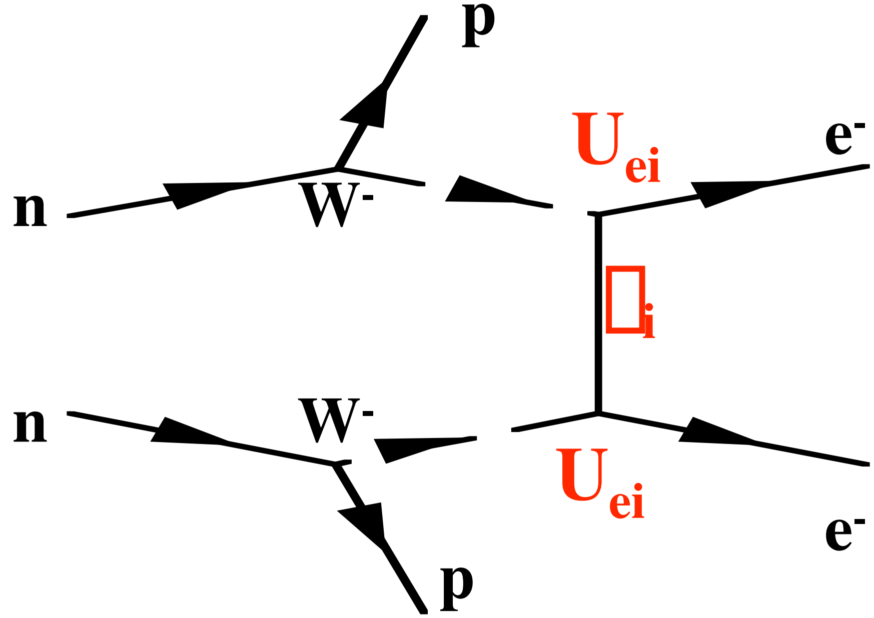
Compare to β decay result:

$$\langle m_\nu \rangle = \sqrt{\sum_{i=1}^{3} \left| U_{ei} \right|^2 m_i^2}$$

real ν emission

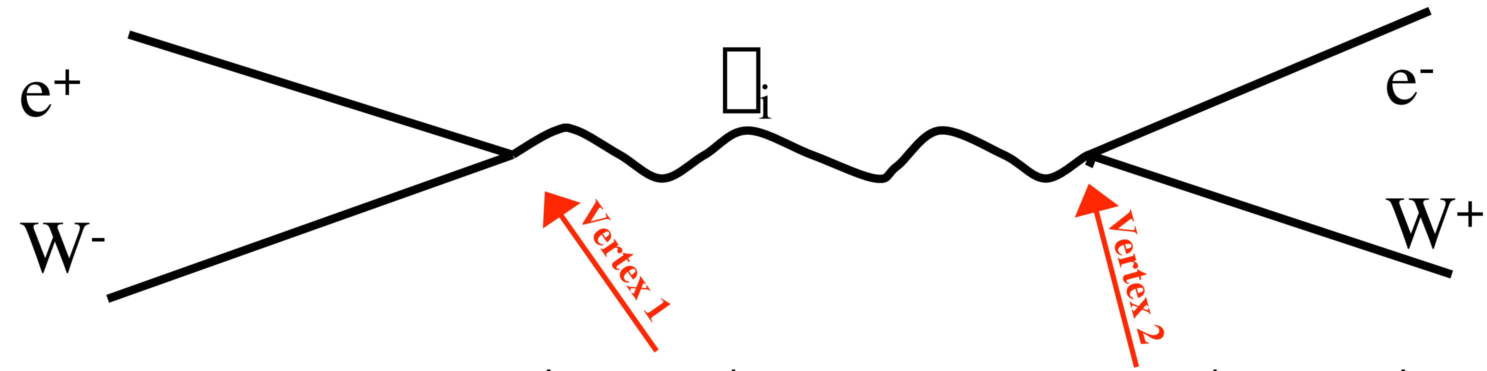
Why does the CP parity appear in <m$_{□□}$>?

$A_{0□}$ □ □$_i$



Look at the critical part of this diagram.

The crossed channel.



$$A \propto \sum_i U_{ei}^2 \langle e^+ W^- | H_{SM} | \nu_i \rangle \langle \nu_i | H_{SM} | e^- W^+ \rangle$$

The 1st vertex creates the CP partner of the particle needed by the 2nd vertex.

$$\textbf{But } CP|\nu_i\rangle = \lambda_i |\nu_i\rangle$$

Upon substitution, the factor λ_i appears.

What can be learned from Oscillations & □□?

From oscillations, we have:

Information on U_{ei}

Information on $\square m^2$

With $<m_{\square\square}>$ constraints, we can constrain m_1:

(2 flavor example)

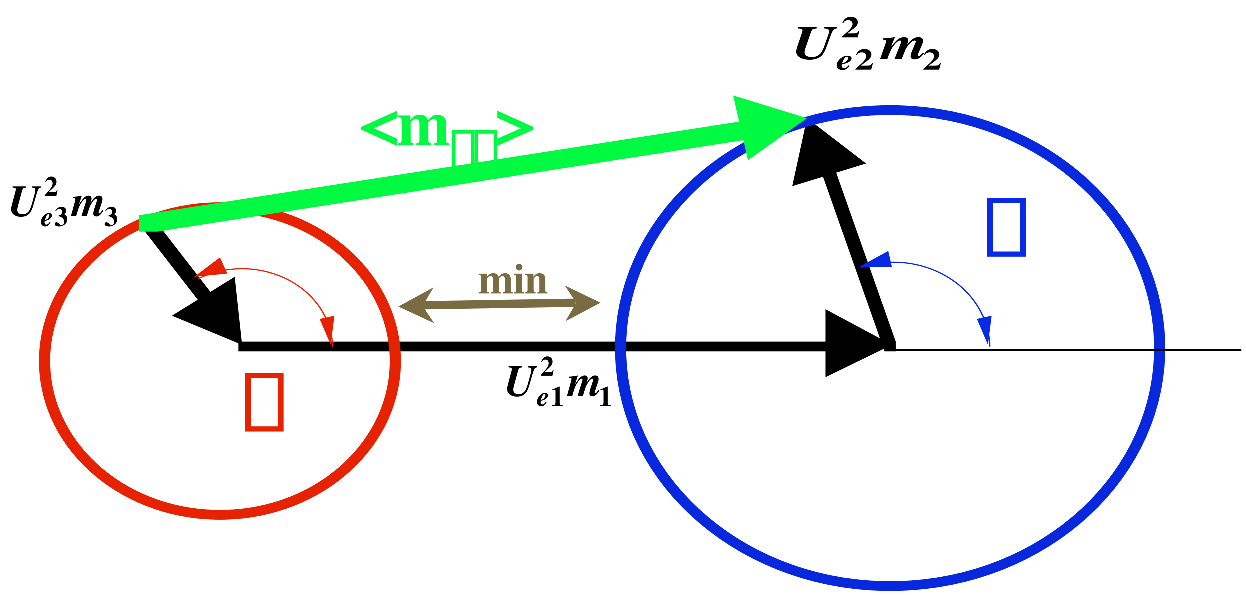
$$\left\langle m_{\square\square} \right\rangle = U_{e1}^2 m_1 + \square_{21} U_{e2}^2 \sqrt{m_1^2 + \square m_{21}^2}$$

Min. <$m_{\beta\beta}$> as a vector sum. General Case

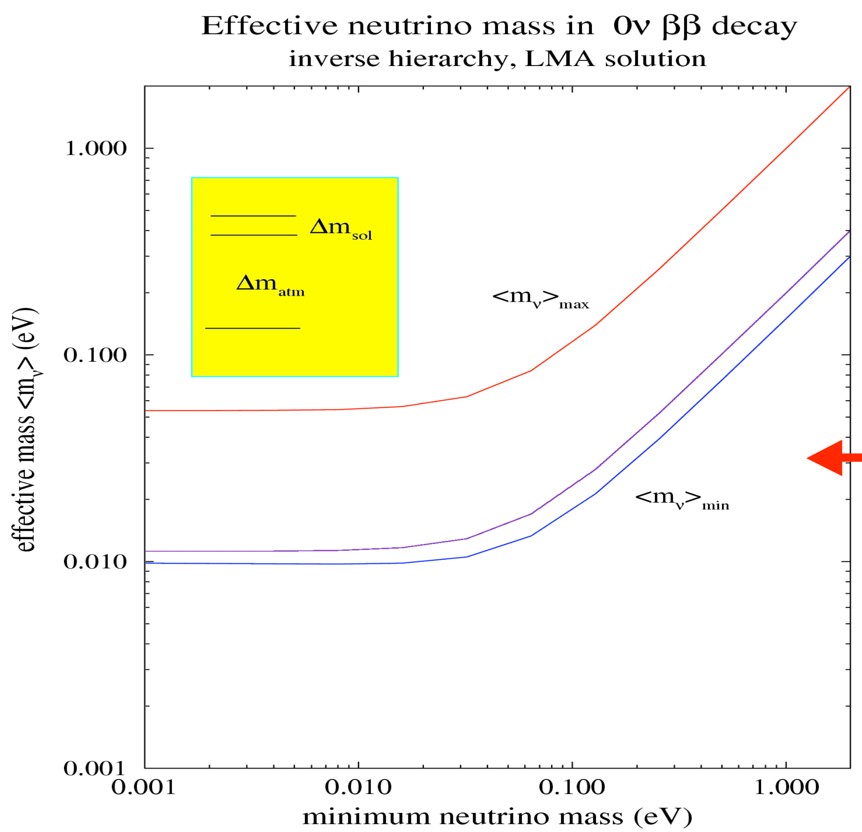
$$\left\langle m_{\beta\beta}\right\rangle = \left\| U_{e1}\right|^2 m_1 + e^{i\alpha}\left|U_{e2}\right|^2 m_2 + e^{i\beta}\left|U_{e3}\right|^2 m_3 \right\|$$

<$m_{\beta\beta}$> is the modulus of the resultant.

In this example, <$m_{\beta\beta}$> has a min. It cannot be 0.



More General: 3 ν



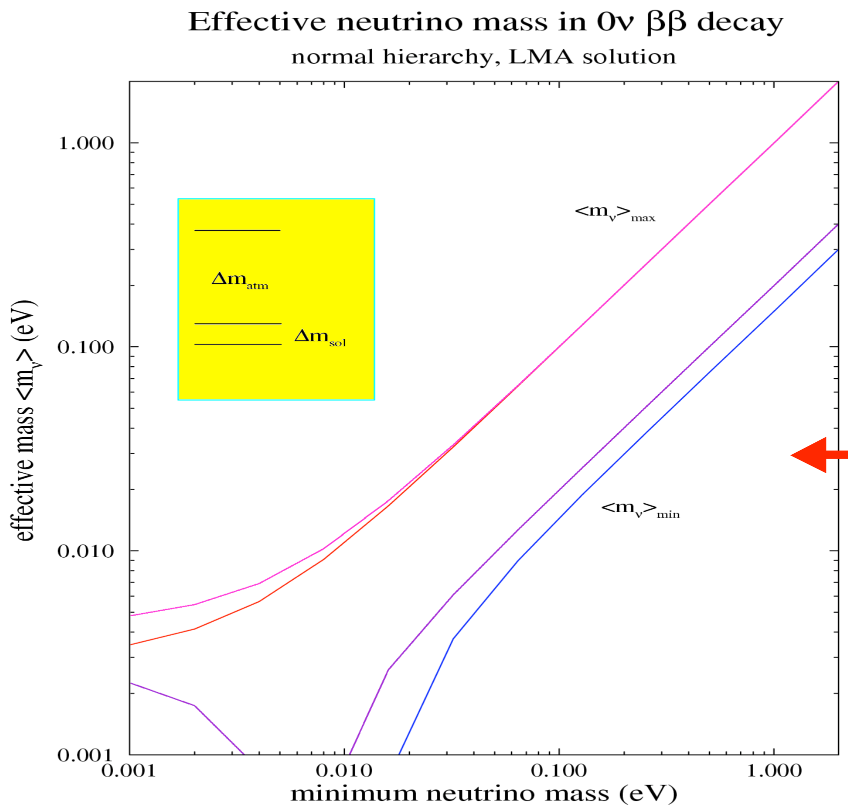
$<m_{\beta\beta}>$

$m_{smallest}$

30 meV or few x 10^{27} yr

Plot Thanks to Petr Vogel

More General



30 meV or few x 10^{27} yr

Plot Thanks to Petr Vogel

An exciting time for ββ!

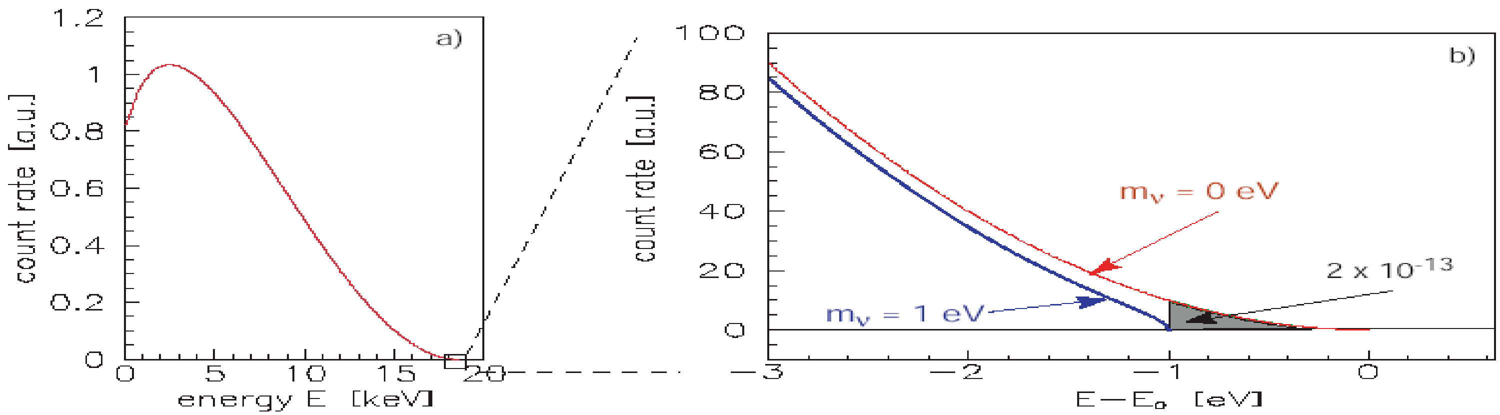
For at least one neutrino: $m_i > \sqrt{\Delta m^2_{atmos}} \approx 50 meV$

For the next experiments: $\langle m_{\beta\beta} \rangle \approx 50 meV$

< m$_{\beta\beta}$ > in the range of 10 - 50 meV is very interesting.

The Neutrino Mass from β decay

The shape of the β energy spectrum near the endpoint depends on m_ν.



$$\langle m_\nu \rangle = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2} < 2.2 \text{ eV}$$

KATRIN LOI

NP B (Proc. Suppl.) 91 (2001), 273

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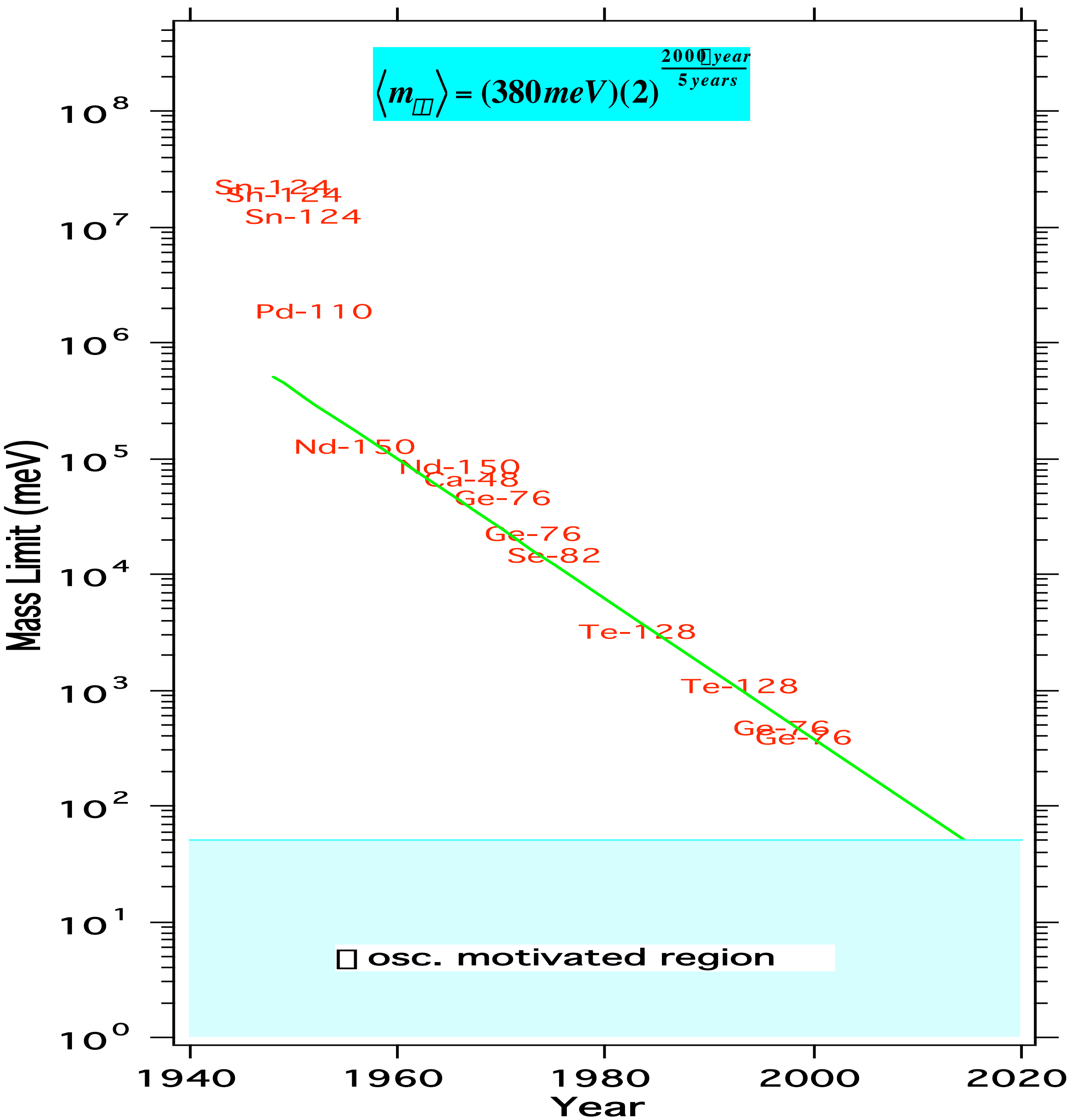

<m$_{\beta\beta}$> History

|M| Reference
Eur. Lett. 13, 31 (1990)

Presently

<m$_{\beta\beta}$> < 300 meV

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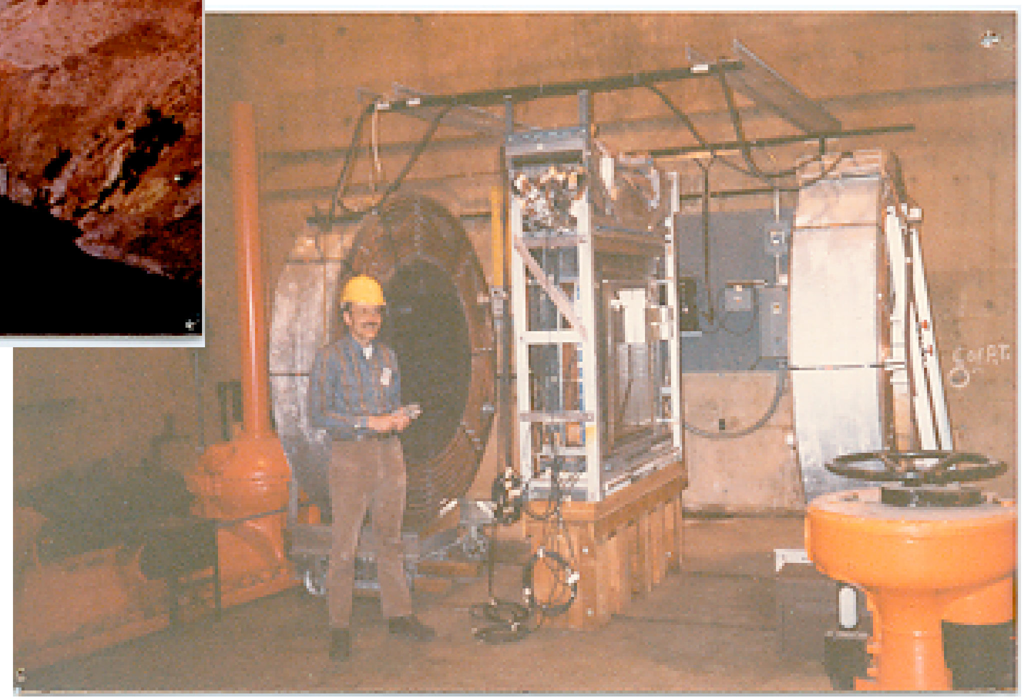
The 1st Observation



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Present Experimental Limits

$$\langle m_{\beta\beta} \rangle = \left[\frac{1}{|M| \sqrt{G_{0\nu} T_{1/2}}} \right]$$

	Half Life	$\langle m_{\beta\beta} \rangle$
Ge (IGEX) NP of RAS 63, 1299 (2000)	160×10^{23} y	~330 meV
Ge (Heid-Mosc) Dark Matter 2000	190×10^{23} y	~300 meV
Mo (ELEGANTS) NP A611, 85 (1996)	0.52×10^{23} y	~6600 meV
Te-130 (Cuoricino) PL B486, 13 (2000)	1.44×10^{23} y	~1700 meV
Te-128 (Geochem) PR C47, 806 (1993)	6.9×10^{24} y	~1100 meV
Xe (Gotthard) PL B 434, 407 (1998)	4.4×10^{23} y	~2500 meV

An Ideal Experiment

Maximize Rate/Minimize Background

$$\langle m_{\beta\beta} \rangle \propto \left(\frac{b \Delta E}{M t_{live}} \right)^{\frac{1}{4}}$$

Large Mass (~ 1 ton)

Good source radiopurity

Demonstrated technology

Natural isotope

Small volume, source = detector

Good energy resolution

Ease of operation

Large Q value, fast $\beta\beta(0\nu)$

Slow $\beta\beta(2\nu)$ rate

Identify daughter

Event reconstruction

Nuclear theory

A Great Number of Proposed Experiments

COBRA	Te-130	10 kg CdTe semiconductors
DCBA	Nd-150	20 kg Nd layers between tracking chambers
NEMO	Mo-100, Various	10 kg of ββ isotopes (7 kg of Mo)
CAMEO	Cd-114	1 t $CdWO_4$ crystals
CANDLES	Ca-48	Several tons CaF_2 crystals in liquid scint.
CUORE	Te-130	750 kg TeO_2 bolometers
EXO	Xe-136	1 ton Xe TPC (gas or liquid)
GEM	Ge-76	1 ton Ge diodes in liquid nitrogen
GENIUS	Ge-76	1 ton Ge diodes in liquid nitrogen
GSO	Gd-160	2 t Gd_2SiO_5:Ce crystal scint. in liquid scint.
Majorana	Ge-76	500 kg Ge diodes
MOON	Mo-100	Mo sheets between plastic scint., or liq. scint.
Xe	Xe-136	1.56 t of Xe in liq. Scint.
XMASS	Xe-136	10 t of liquid Xe

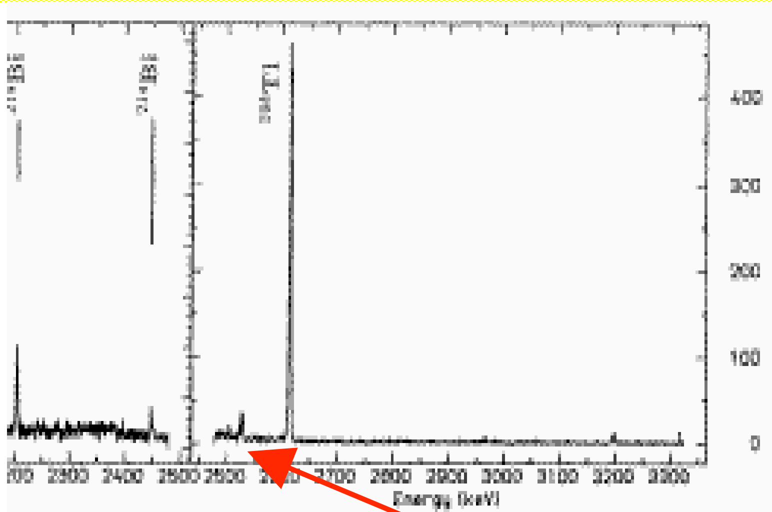
Summary of Proposals

	Proposed ton-year = M * T * □	Anticipated $\langle m_{ee} \rangle$, (QRPA)
CUORE	**0.21*5*1 = 1**	**60 meV**
EXO	**6.5*10*0.7 = 45**	**13 meV**
GENIUS	**1*2*1 = 2**	**20 meV**
MAJORANA	**0.5*10*1 = 5**	**25 meV**
MOON	**3.3*3*0.14 = 1.4**	**30 meV**

The $\langle m_{□□} \rangle$ limits depend on background assumptions and matrix elements which vary from proposal to proposal.

“Found” Peaks

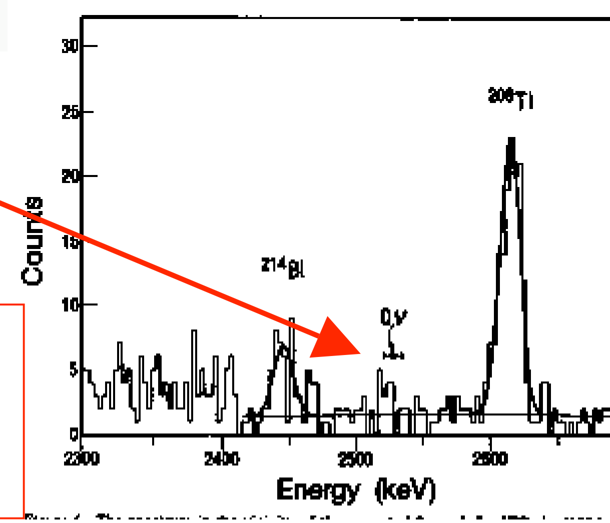
PR D45, 2548 (1992)



Need more than one experiment

A 2527-keV Ge-det. peak that was an electronic artifact.

A ~2528-keV Te-det. peak that was a 2σ Statisticalflucuation.



NP B35 (Proc. Supp.), 366 (1994).

Classes of Background for □□(0□)

□□(2□) tail

Need good energy resolution.

Natural U, Th in source and shielding

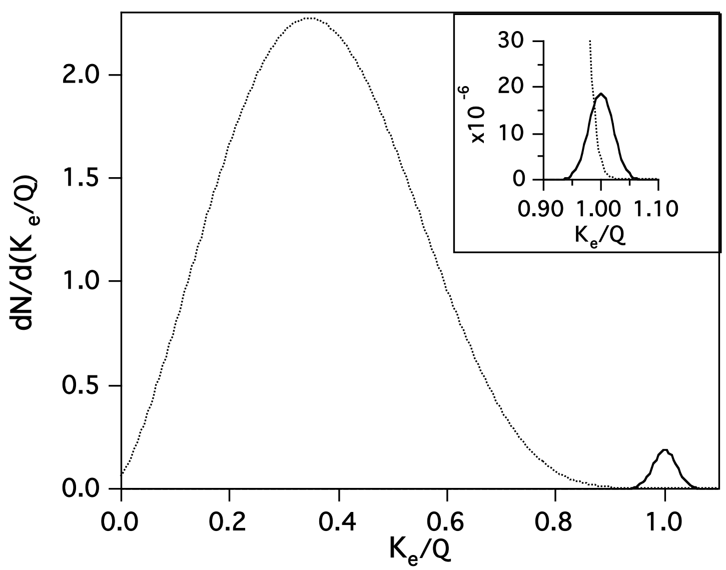
Pure materials, segmentation, pulse shape.

Cosmic ray activation

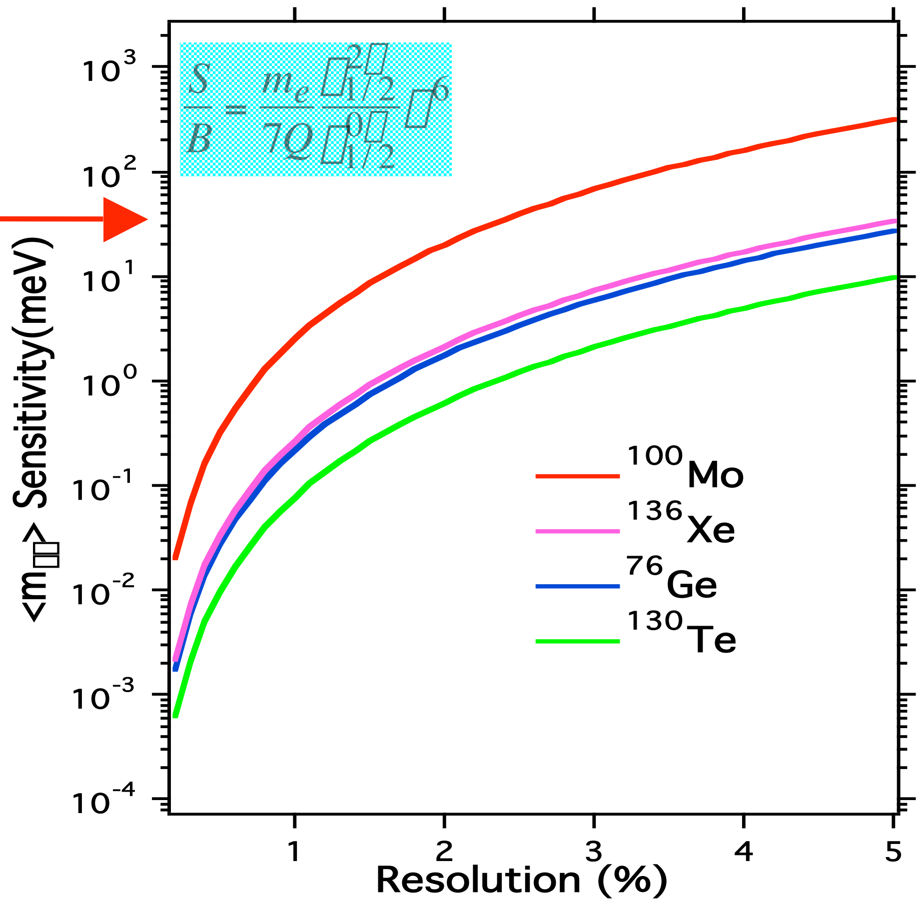
Store and prepare materials underground.

$\beta\beta(2\nu)$ as a Background.

Sum Energy Cut Only



next generation experimental goal



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Natural Activity

The Problem:

τ(U, Th) ~ 10^{10} years

Goal: $\tau(\beta\beta(0\nu)) \sim 10^{27}$ years

Detector: Intrinsic Ge is very pure

Cryostat: Electro-formed Cu

Shielding: Roman Pb

Front End Electronics: behind shield

Cosmic Ray Induced Activity

Material dependent.

Lots of experience with Ge.

Need for depth to avoid activation.

Need for storage to allow activation to decay.

The Majorana Project

Duke U.
North Carolina State U.
TUNL
Argonne Nat. Lab.
JINR, Dubna
ITEP, Moscow
LLNL
New Mexico State U.
Pacific Northwest Nat. Lab.

U. of Washington
LANL
U. of South Carolina
Brown
Univ. of Chicago
RCNP, Osaka Univ.
Univ. of Tenn.
Oak Ridge Nat. Lab.

We are looking for students & postdocs!

Majorana Overview

0.5 ton of 86% enriched ^{76}Ge

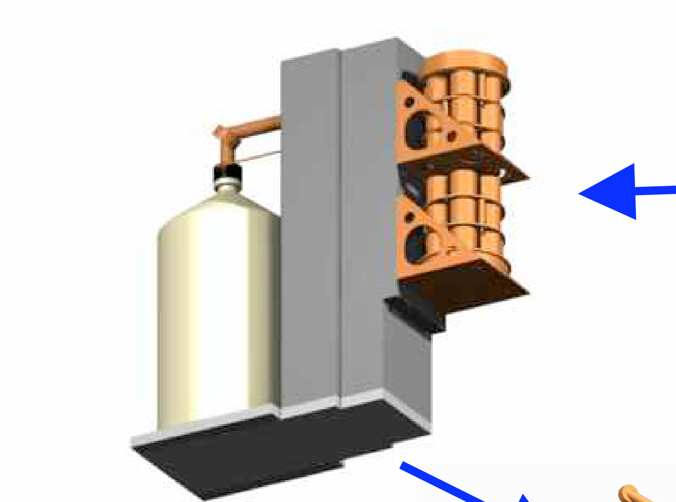
Segmented detectors using pulse shape discrimination to improve background rejection.

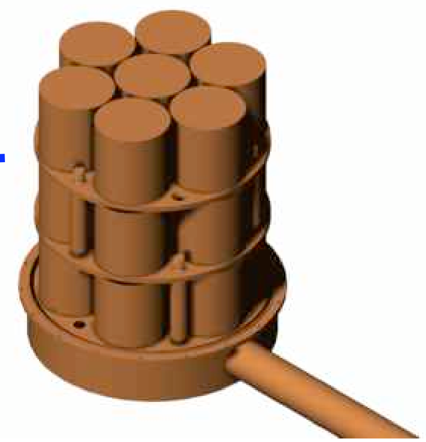
Prototypes being assembled. (18 crystal array, 1 enriched segmented detector)

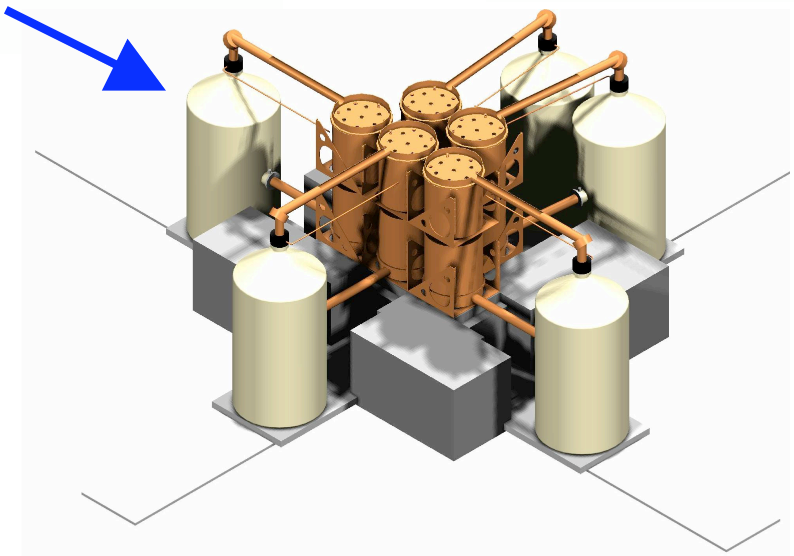
Highly efficient

IGEX is an effective prototype

Majorana Layout







Molybdenum Observatory Of Neutrinos - MOON

U. of Washington

U. of North Carolina

U. of Wisconsin

Research Center for Nuclear Physics, Osaka

Plus others as collaboration is forming.

Spokesperson
Hiro Ejiri
RCNP

MOON Overview

3.3 tons ^{100}Mo, 34 tons Mo

Doesn’t require enriched material (but would want it).

Scintillator/source sandwich

Or possibly bolometer

Position and single $E_{□}$ data play big role in □□(2□) and U, Th rejection.

14% efficiency

ELEGANTS is precursor.

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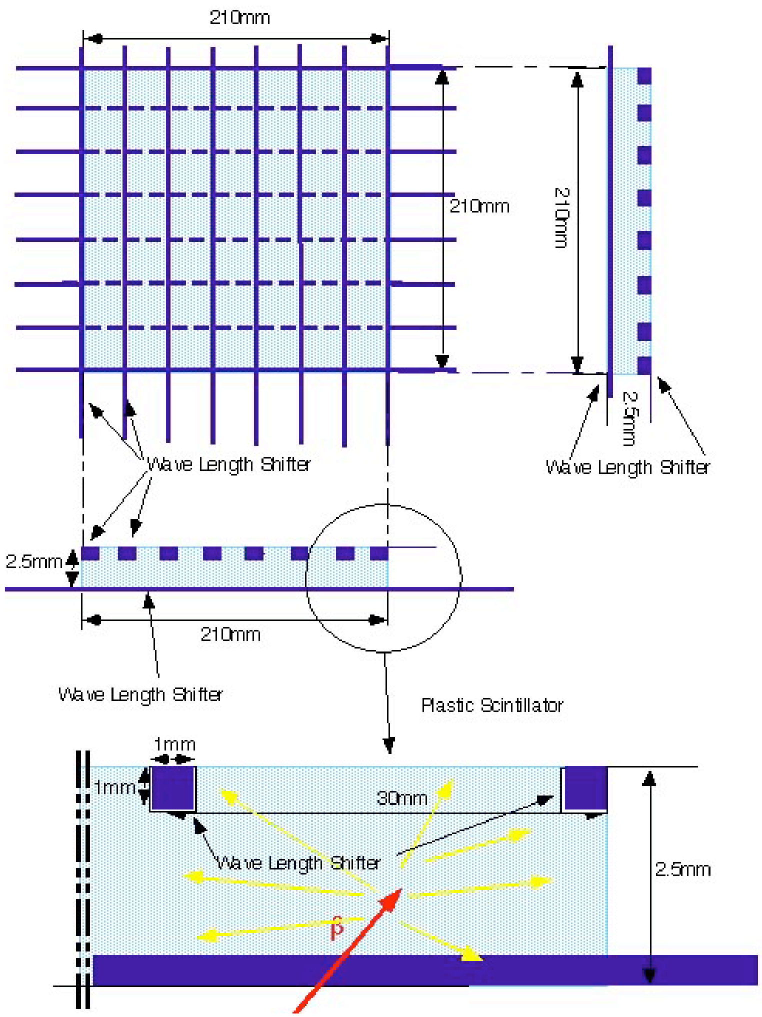
MOON Scintillator



Cryogenic Underground Observatory for Rare Events - CUORE

Berkeley
Firenze
Gran Sasso
Insubria (COMO)
Leiden
Milano
Neuchatel
U. of South Carolina
Zaragoza

Spokesperson
Ettore Fiorini
Milano

CUORE Overview

0.21 ton, 34% natural abundance ^{130}Te

TeO_2 bolometers, 750 g crystals

Doesn't require enriched material.

1020 5x5x5 cm^3 crystals

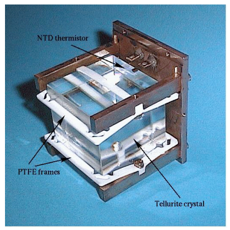
25 towers of 10 layers of 4 crystals

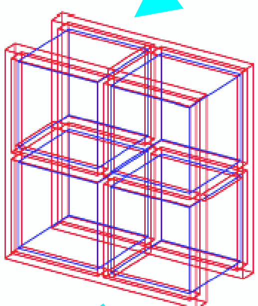
Gran Sasso Laboratory

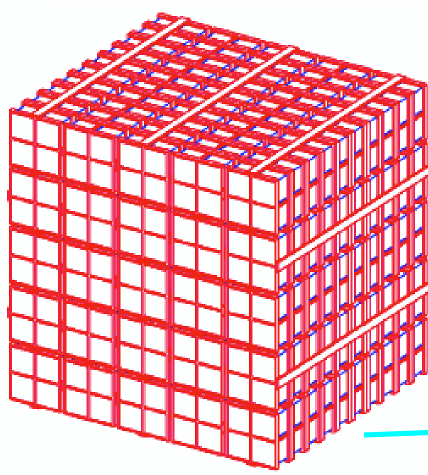
CUORICINO is an approved prototype (1 tower).

CUORICINO began operation in Feb. 2003

CUORE Detector



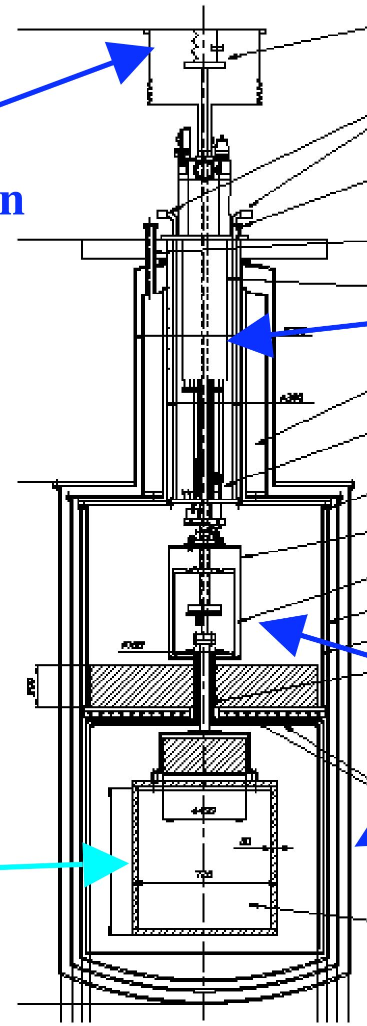




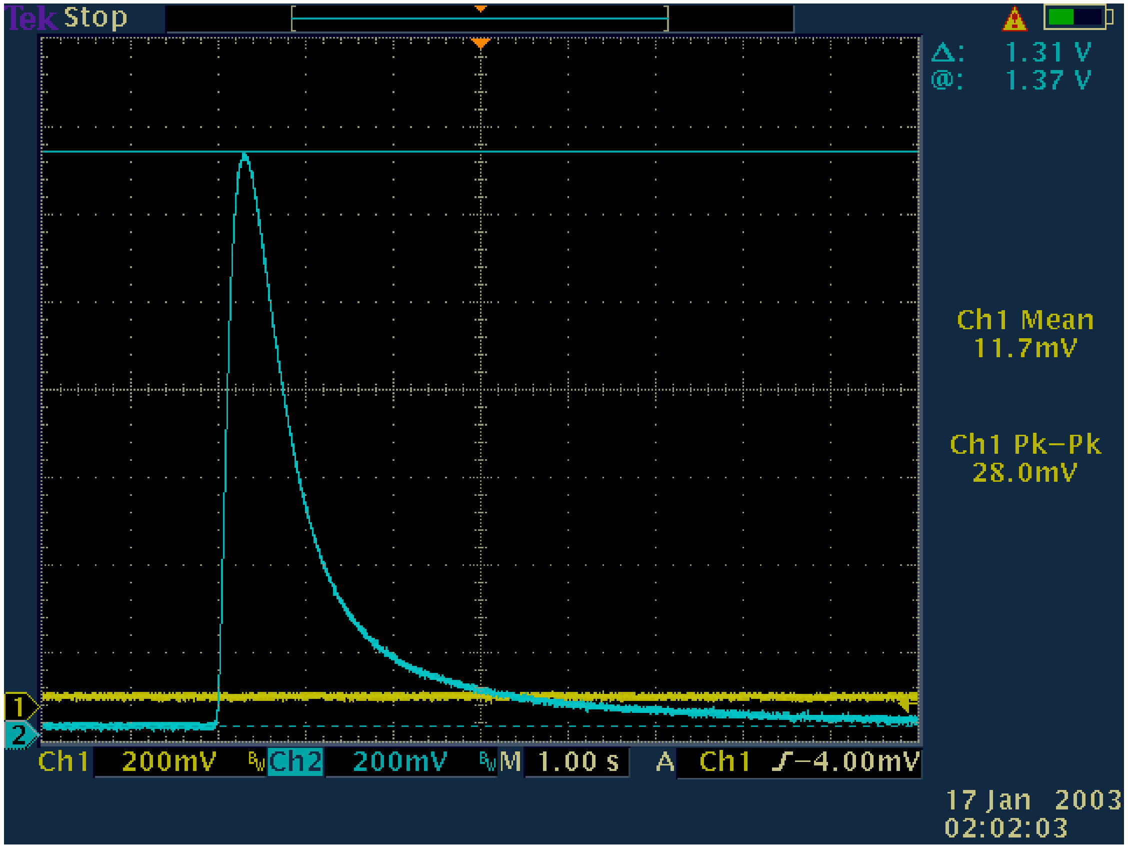
Detector Damping Suspension

Dilution Unit

Thermal Shields



CUORICINO IS OPERATING



FIRST PULSE.

Data runs began In Feb. 2003

Enriched Xenon Observatory - EXO

U. of Alabama
Caltech
IBM Almaden
ITEP Moscow
U. of Neuchatel
INFN Padova
SLAC
Stanford U.
U. of Torino
U. of Trieste
WIPP Carlsbad

Spokesperson
Giorgio Gratta
Stanford

EXO Overview

10 ton, ~70% enriched ^{136}Xe

70% effic., LXe chamber

Optical identification of Ba ion.

- Extract ion on cold probe to optical trap.

Has achieved ~2% energy resolution

- Measure ionization and scintillation

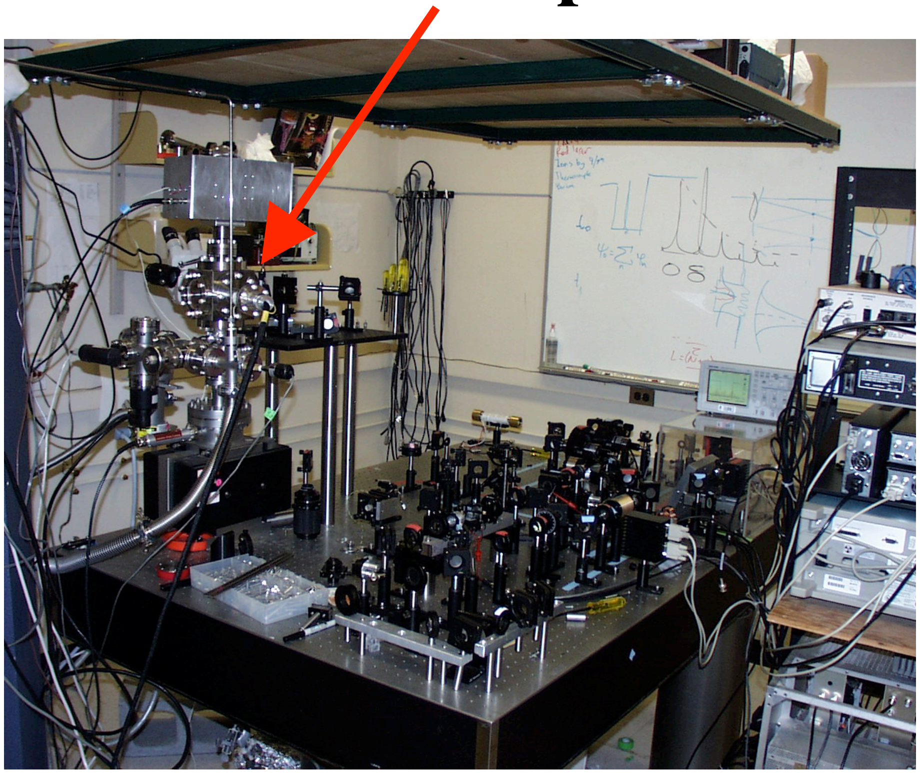
TPC performance similar to that at Gottard.

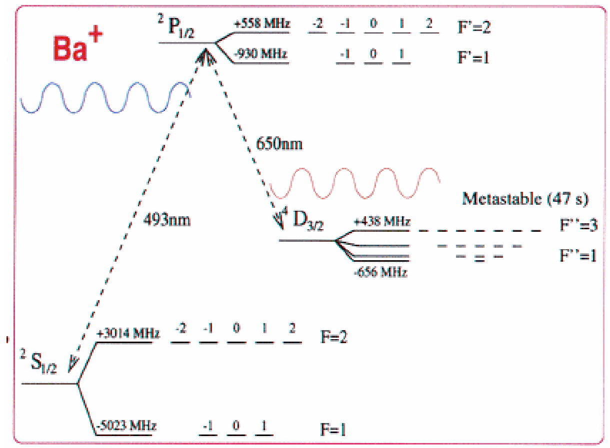
~200-kg ^{enr}Xe prototype (no Ba ID)

- Isotope in hand

Stanford Optics Lab with Ba Trap

Ba Trap



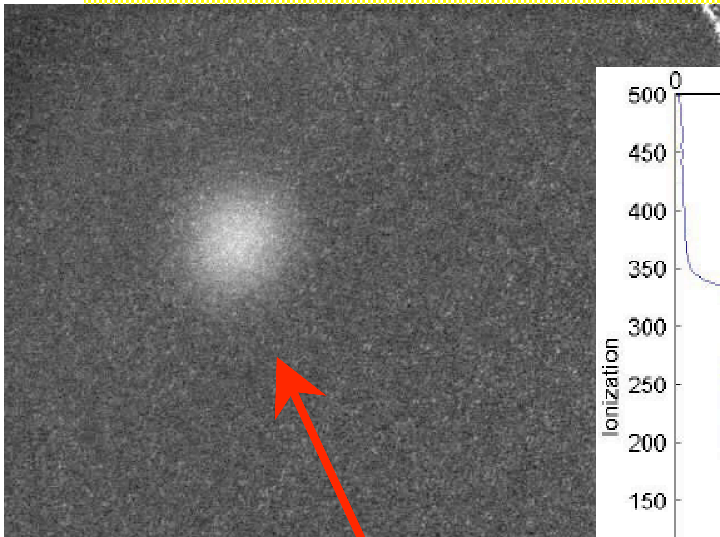


$^{136}Xe \rightarrow ^{136}Ba^{++} e^- e^- \rightarrow ^{136}Ba^{+}$

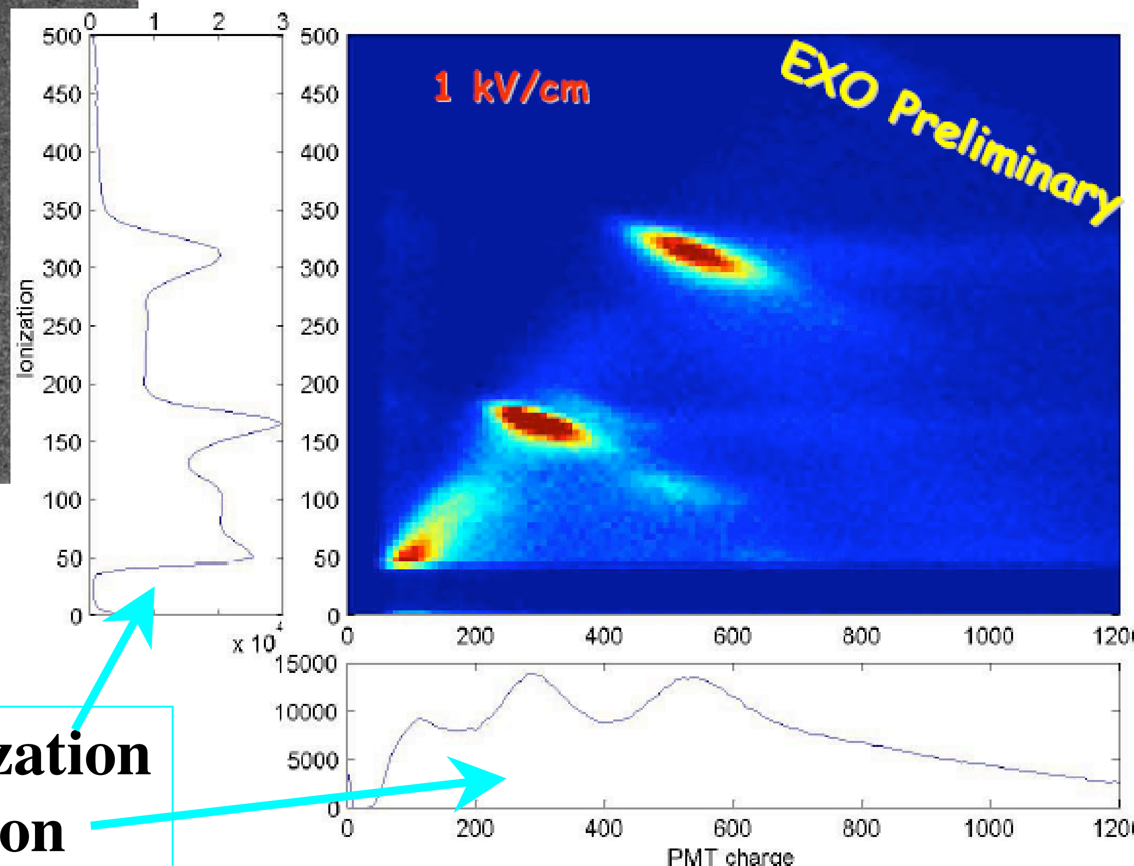
Optically observe final state.

(Moe, PRC44 (1991) 931)

EXO lone Ion/Resolution



Single Ba ion



Measure ionization and scintillation

GErmanium NItrogen Underground Setup - GENIUS

MPI, Heidelberg

Kurchatov Inst., Moscow

Inst. Of Radiophysical Research, Nishnij Novgorod

Braunschweig und Technische Universität, Braunschweig

U. of L'Aquila, Italy

Int. Center for Theor. Physics, Trieste

JINR, Dubna

Northeastern U., Boston

U. of Maryland, USA

University of Valencia, Spain

Texas A & M U.

Spokesperson
Hans Klapdor-Kleingrothaus
MPI

GENIUS

GENIUS Overview

1 ton, ~86% enriched ^{76}Ge

Naked Ge crystals in LN

Very little material near Ge.

1.4x10^6 liters LN

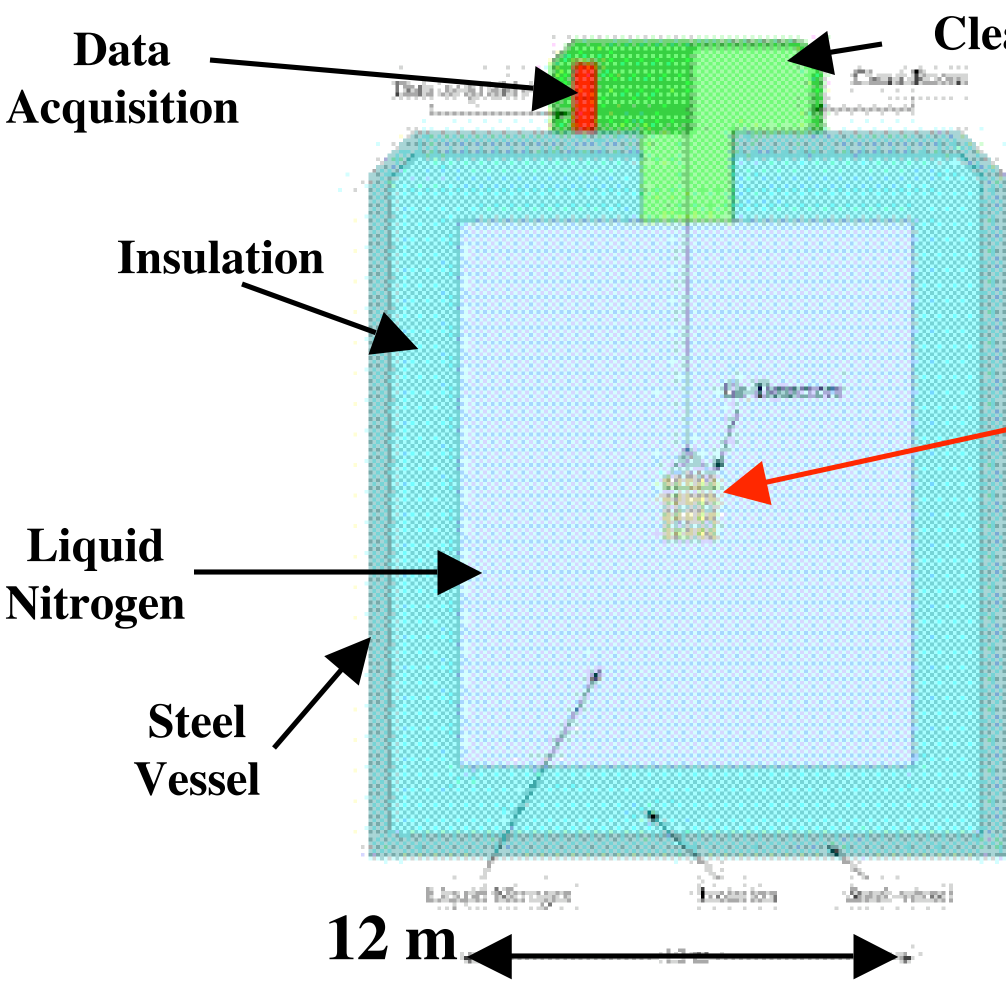
40 kg test facility is approved.

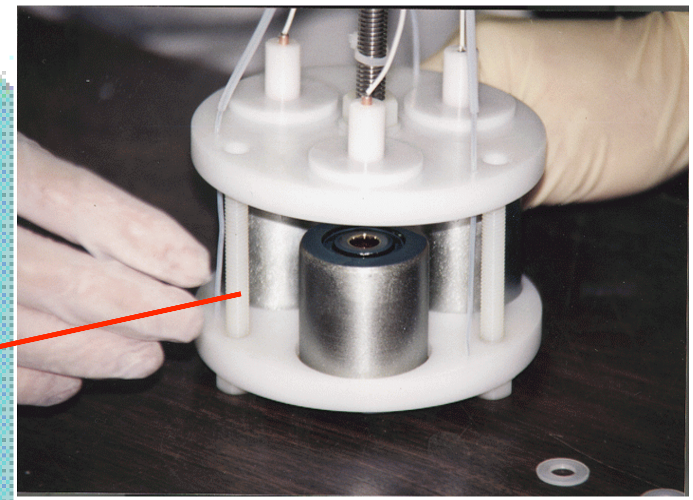
highly efficient

Heid.-Moscow experiment is precursor

GENIUS

GENIUS Layout





Setup for operation of three 'naked' Germanium detectors in liquid nitrogen.

GENIUS

To interpret □, one needs Matrix Elements

$$\frac{1}{\Box_{0\Box}} = G_{0\Box}\left|M_{0\Box}\right|^2 \left\langle m_{\Box\Box} \right\rangle^2$$

There are many calculations.

Most authors quote mass limits derived from representatives of the whole range.

How do we interpret the uncertainty associated with the nuclear physics?

$\langle m_{\beta\beta} \rangle$ Uncertainties

Imagine signal at 7×10^{26} years

500 kg for 10 years (~100 meV)

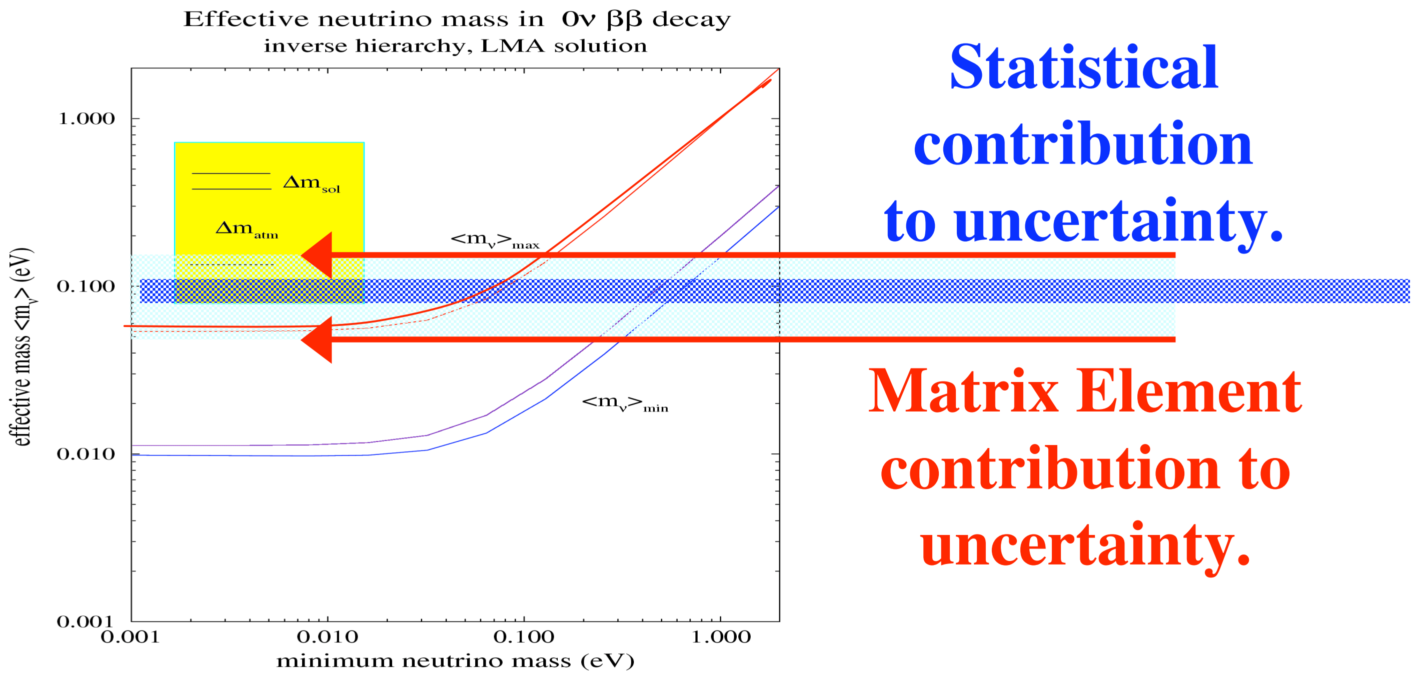
- **~50% unc. for $T_{1/2}$ (with BG)**
- **~20% without BG**

$$\frac{\delta m}{m} = \frac{1}{2}\frac{\delta T}{T}$$

|M| Range: 50-160 meV

Statistics (with BG): ±25 meV

Consider a 100 meV result.



Statistical contribution to uncertainty.

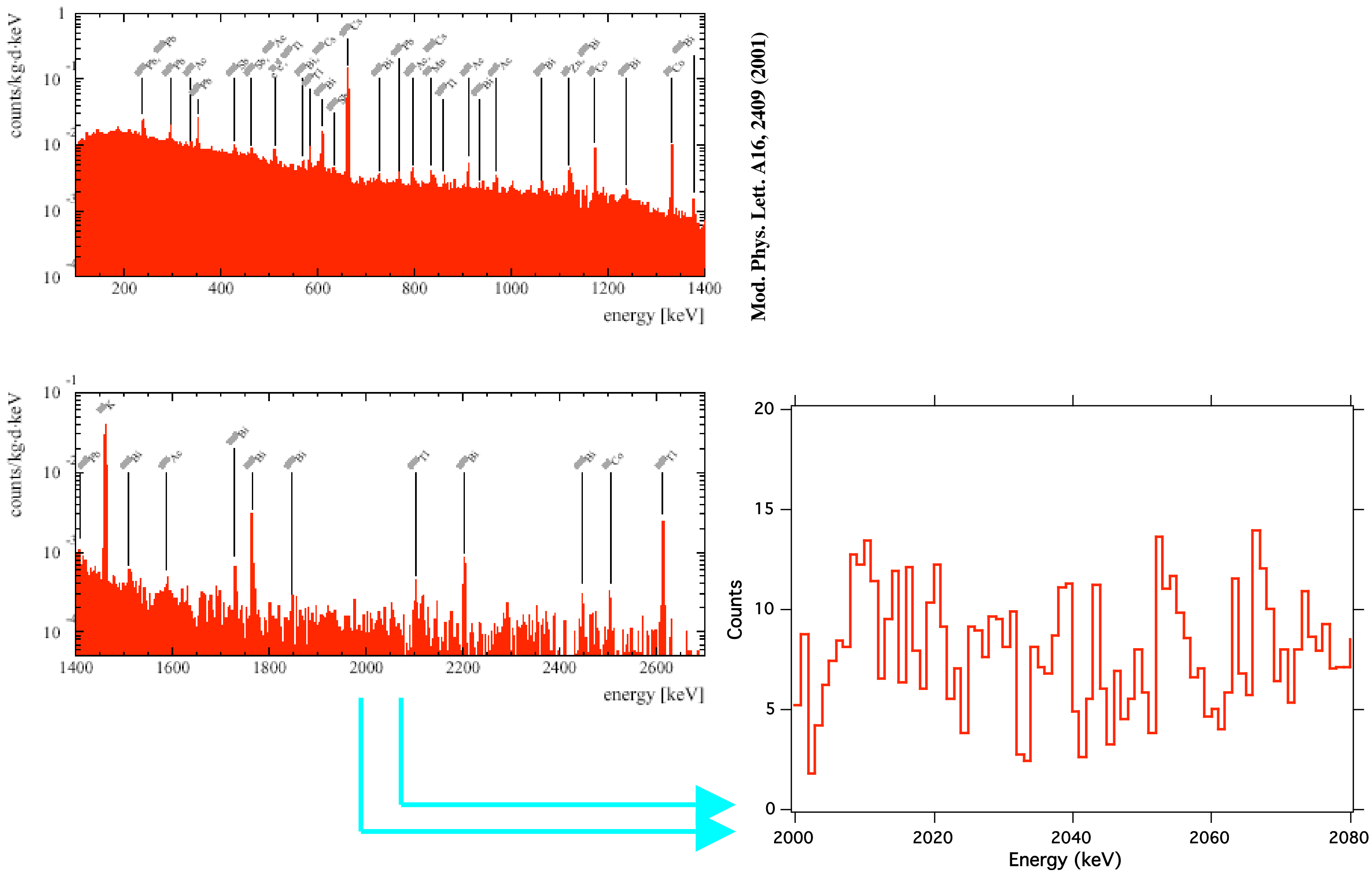
Matrix Element contribution to uncertainty.

Would this exclude the inverted hierarchy with small $m_{smallest}$?

Need improvement in the Theory.

Steve Elliott

A Recent Claim for □□(0□)



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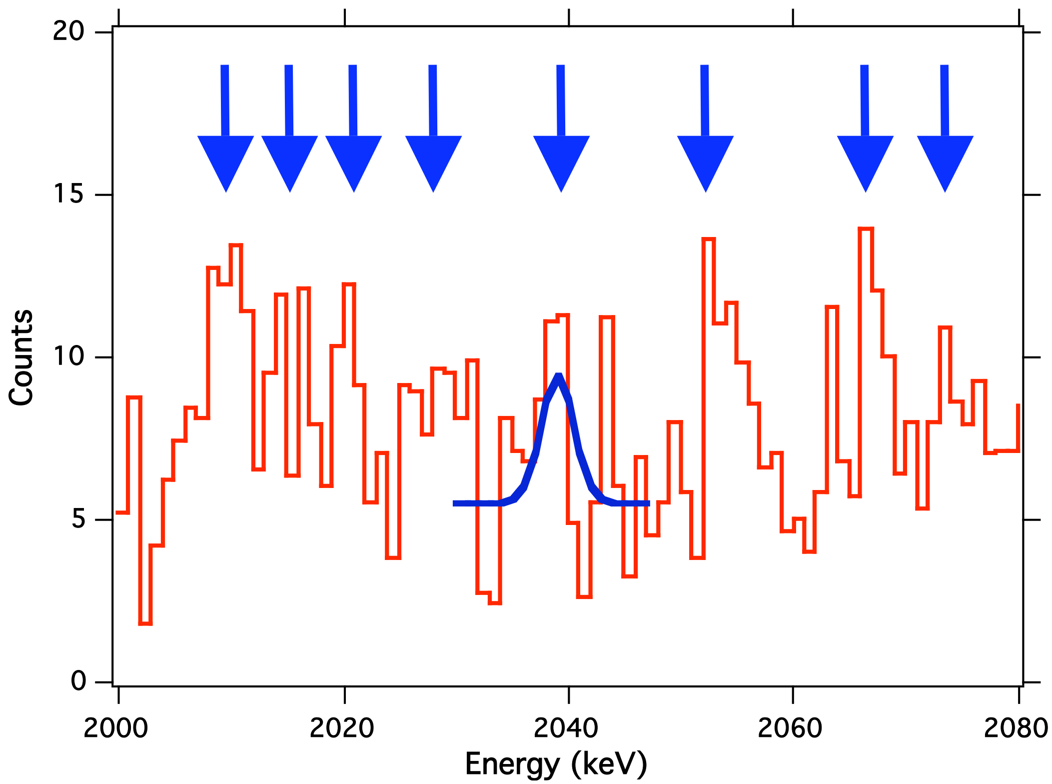
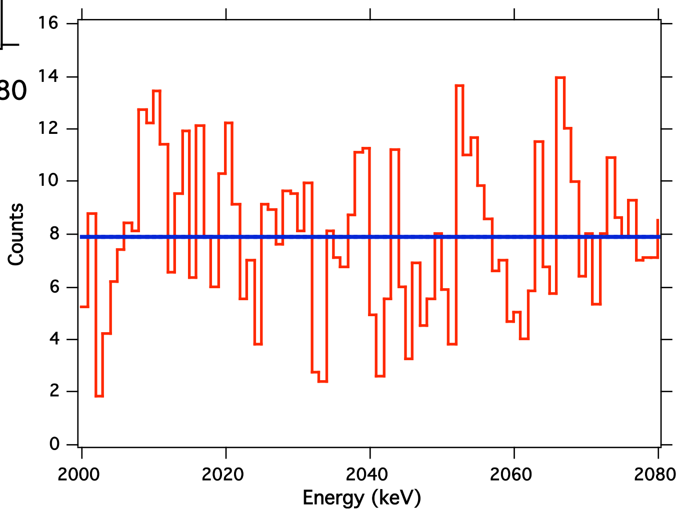
The Analysis.



Locations of claimed peaks



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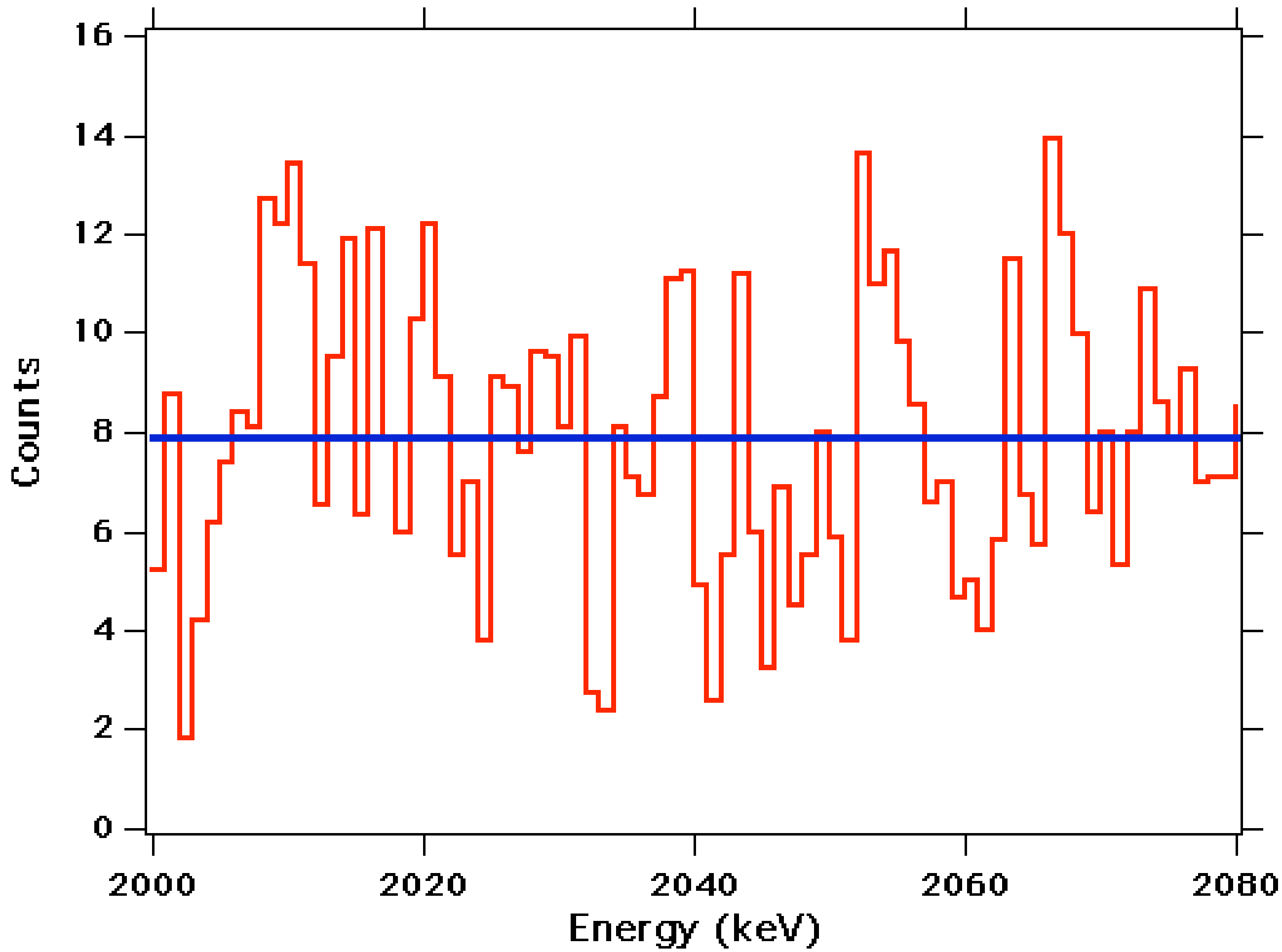
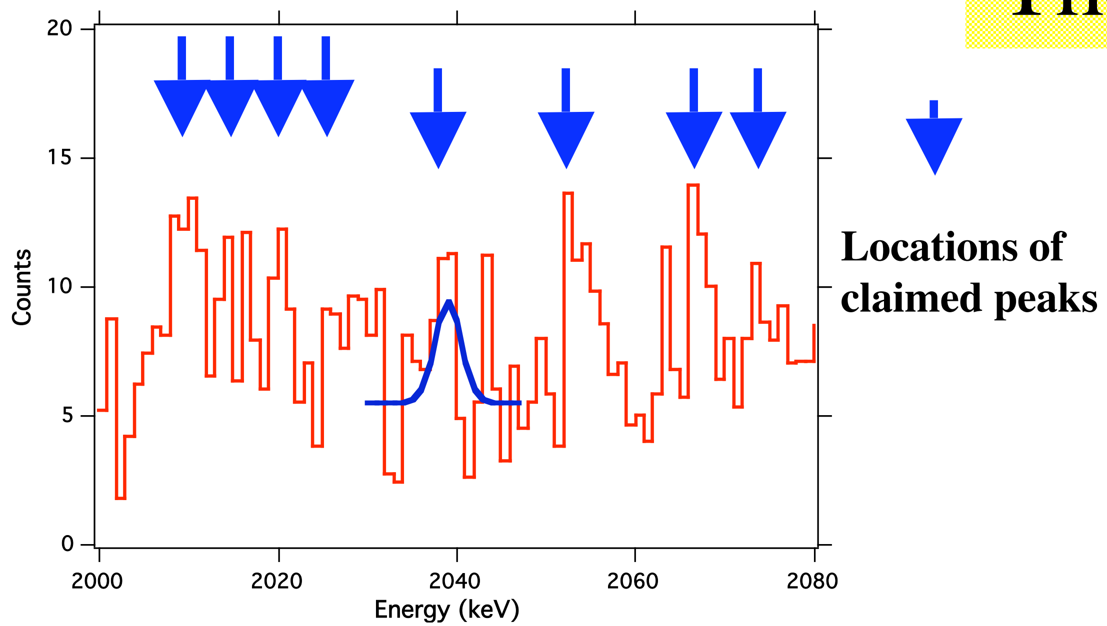
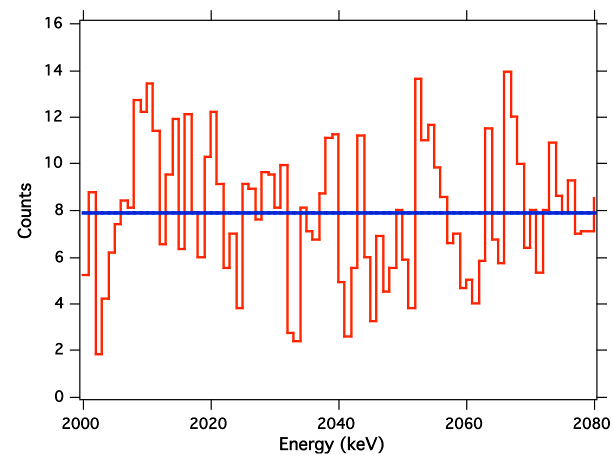


Where are the peaks now?

The Controversy.





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If one had to summarize the controversy in a short statement:
Consider two extreme background models:

1. **Entirely flat in 2000-2080 keV region.**
2. **Many peaks in larger region, only □□ peak in small region.**

These 2 extremes give very different significances for peak at 2039 keV.
KDHK chose Model 2 but did not consider a systematic uncertainty associated with that choice.

Conclusion

Due to the minimum neutrino mass scale implied by the neutrino oscillation experiments:

The next generation $\beta\beta$ experiments have a good possibility of reaching an exciting $\langle m_{\beta\beta} \rangle$ region.